Continuous Observation and Evaluation of Photovoltaic Power Generation Systems for Residential Buildings in Japan

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ABSTRACT

We discuss in this paper the method to evaluate the performance of photovoltaic (PV) generation systems, without additional cost to PV owners, and the result of its application to continuously generated data of PV systems for residential buildings in Japan.

From 1997 to1998, sponsored by the Tokyo Electric Power Company, a grid-connected PV system was installed onto the roof-tops of one hundred and thirty-two detached houses in the Tokyo area. The performance of the system was measured from its installation until September 2000; and consequently, in 2001, approximately ninety PV owners established an organization called the Clean Energy Life Club (CELC), due to issues concerning long-term utilization that had arisen from the performance measurements collected.

Since June 2001, each of the CELC members has checked PV output once a month, by watching an indicator on a power conditioner, and reported the value to the Jyukankyo Research Institute (JYURI). To evaluate the actual PV output, PV output was estimated from meteorological data through newly developed formulas and the outcome of existing studies. The performance of the PV system was evaluated as a monthly or annual "PV output index", which was an actual PV output at the time of setting an estimated value to 100.

Although PV systems have generally worked well, some systems demonstrated performance degradation in 2002. In two cases we performed field investigations with a manufacturer to check the systems. The manufacturer replaced the modules in which the deterioration was found, and the effect of this replacement was shown as a recovery of "PV output index".

Introduction

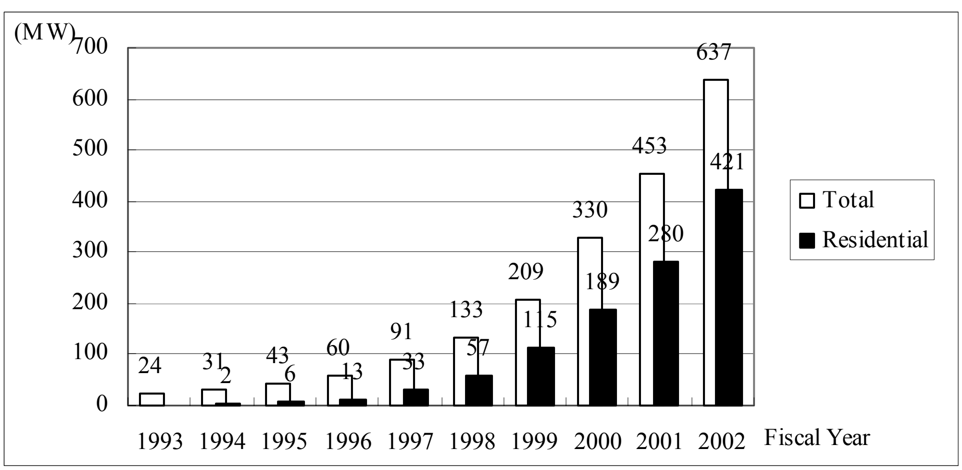
The utilization of photovoltaic (PV) power generation system is an effective measure for coping with global warming. In fact, since 1994, the Japanese government has established PV system installation subsidy program for residential buildings to decrease the cost of installation and meet a capacity goal of 4,800MW by 2010. Through this program, as shown in **Figure 1**, the capacity of installed PV systems has reached 637MW in total, 421MW of which in residential buildings. Though the amount is only 13% of the goal, it is the largest in the world and accounts for 48% of major IEA countries (see **Figure 2**).

Figure 3 shows that the cost of installation has been reduced by 19% to approximately $6.50 per Watt since 1993. Also, the cost of PV generation has been reduced to $0.45 per kWh, which is twice as high as the price of electricity for residential buildings; and, in addition to this, the electric power companies contribute to support the diffusion by continuing to buy out surplus electricity at a rate equal to their selling price.

As a decade has passed since PV systems have been commercially used, more PV owners are interested in its performance and reliability for long-term use. Jahn and Nasse (2003) showed operational performance results of over three hundred grid-connected PV systems from fourteen IEA countries. In their paper, they indicated that the average performance ratio of systems installed in the early 1990s in Germany reduced by 11% between 1993 and 2000. On the other hand, systems installed since 1997 have shown a better and stable performance.

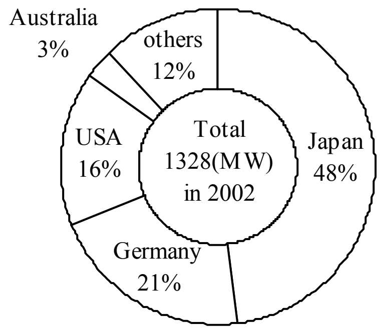
The datasets they used, which can be downloaded as a database program from the website of IEA/PVPS Task2 (www.task2.org), have a number of monitoring items, such as output from arrays and inverters, total solar radiation, array temperatures, and performance ratios. This information could be helpful to PV owners interested in knowing more about system performance. However, it is too expensive PV owners to collect this data by themselves, but, it is imperative for them to find how to evaluate the performance of their PV system without additional costs. In this paper we propose a method of evaluation, which uses both the indicated PV output values in power conditioners or remote controllers and the estimated total solar radiation from meteorological data available to the public.

Figure 1. Cumulative Installed PV Generation System in Japan



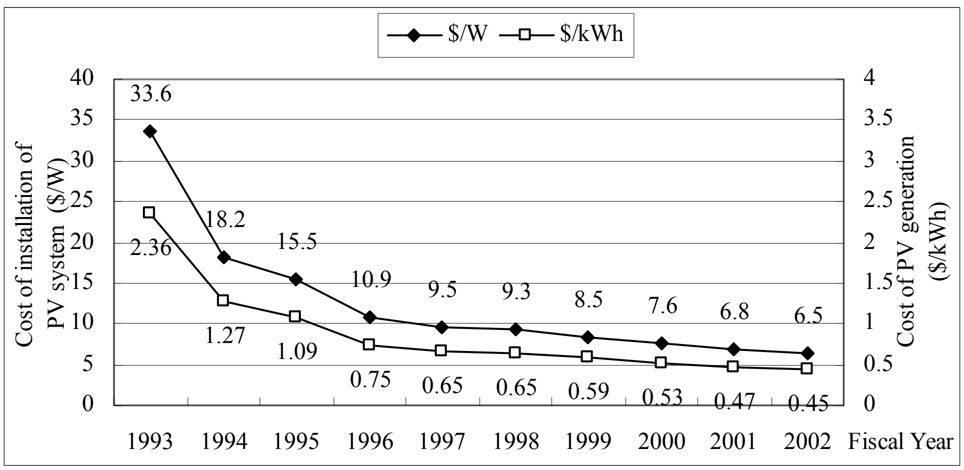
Source: Ministry of Economy, Trade and Industry (METI)

Figure 2. Cumulative Installed PV Generation Systems in 20 IEA Countries in 2002



Source: IEA-PVPS (2003)

Figure 3. Cost of Installation and PV Generation for Residential Buildings



Source: Ministry of Economy, Trade and Industry (METI)
Note: exchange rate 1$ = ¥110

Clean Energy Life Club (CELC)

In 1997, apart from the government program, the Tokyo Electric Power Company (TEPCO) started a monitoring program which granted subsidies to the members of the Seikatsu Club Consumers' Cooperative (CO-OP) in the Tokyo/Kanagawa area, who were planning to install grid-connected PV systems on the rooftops of detached houses.

The program consists of three phases of monitoring households: 1) subsidy for installation, 2) measurement survey followed by complete installation, 3) questionnaire surveys focused on attribution and consciousness of energy consumption. From 1997 to 1999, out of three hundred and seventy-six applicants one hundred and thirty-two households were selected to be monitored. Approximately one-half of the installation cost was subsidized. After installation, hourly PV output, electricity consumption, electricity purchased and sold for all systems, global solar radiation, and array temperature for 72 systems was collected. These measurements took place until September 2000, and the intermediate result was reported in ACEEE 2000 (Tsurusaki et al (2000)).

After the measurement of the monitoring program was completed in September 2000, it was revealed that one manufacturer had deliberately shipped modules that did not meet a standard of output in standard test condition (STC). In the monitoring program twenty-four of the one hundred and thirty-two systems contained these modules. For these systems whole modules were called back and replaced with the latest high performance modules between December 2000 and March 2001 by the manufacture for free. Another manufacturer also recalled its power conditioner (inverter) during the measurement. These problems made the PV owners uncertain about long-term utilization of PV system.

Therefore, in April 2001, approximately ninety PV owners from the program established an organization named Clean Energy Life Club (CELC) to independently observe long-term performance and hold collective bargaining power for manufacturers.

As shown in **Table 1**, the number of members was ninety-two at the end of February 2004. Ninety members were participants from the monitoring program by TEPCO and COOP, and the remaining two were new comers. Of the ninety members panels of twenty-one members were replaced by new high performance modules as mentioned the above.

Table 1. Members of CELC (February 2004)

	Members from monitoring program		New comers	Total
	Panel not replaced	Panel replaced (*)		
Number of members	69	21	2	92
Total capacity (kW)	214.0	75.3	6.0	295.3
Mean (kW)	3.1	3.6	3.0	3.2

Note: * = Members whose panels were replaced between December 2000 and March 2001.

Evaluation of PV Electric Output

Method

To evaluate the performance of PV system, PV electric output and solar radiation for a panel must be known. In the monitoring program several watt-hour meters and a pyrheliometer were used, but these pieces of equipment were too expensive for many PV owners. Therefore, a method requiring no additional equipment for observation was adopted.

Every power conditioner contains a watt-hour meter and a display to indicate the cumulative amount of PV outputs. By checking the value at the end of each month, a PV owner can get the amount of monthly PV output. In fact, New Energy Foundation (NEF), an organization involved in the establishment and monitoring of the governmental subsidy program, asked recipients to report their PV output by submitting the electricity they purchased and sold, from their utility bill, every six months for two years. Each member of CELC individually checked the value and reported it to JYURI once a month. As this survey started in June 2001, almost all the members did not have PV output data for between October 2000 and May 2001.

Solar radiation for each panel was estimated from meteorological data. Several meteorological observation sites were located in the Metropolitan area. In these sites, four meteorological items: hourly temperature, precipitation, sunshine duration, and wind speed with direction, are automatically observed and collected by the Automated Meteorological Data Acquisition System (AMeDAS). Solar radiation, though no by AMeDAS, is observed, together with other meteorological items including sunshine duration, at sixty-seven meteorological observatories all over the country. The observatory in the Metropolitan area is located in Tokyo.

Hence, an estimation formula of global solar radiation of each month in each meteorological observatory was developed as follows:

$$I_G = a_0 + a_1 S + a_2 I_d + a_3 I_s + a_4 I_d S + a_5 R\sin H + a_6 D\sin H \qquad (1)$$

I_G: global solar radiation (kWh/m^2/h)

S: sunshine duration (h/h)

I_d: direct solar radiation (kWh/m^2/h) *

I_s: diffuse(sky) solar radiation (kWh/m^2/h) *

R: dummy variable of rain fall
(given 1 when precipitation is observed)

D: dummy variable of snow (given 1 when snow depth>0)

H: sun altitude

* theoretical value under fine weather from Berlage formula

The partly estimated result for Tokyo is shown in **Table 2**. The coincidence of formulas was high. As shown in

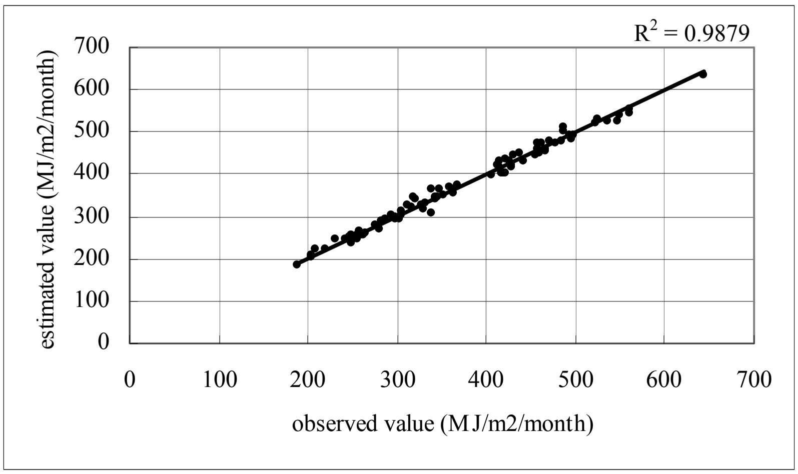
Figure 4, for the monthly global solar radiation counted up hourly, the estimated value was strongly correlated with the observed value.

Table 2. Result of Estimation of Global Solar Radiation (Tokyo)

Month	a0	a1	a2	a3	a4	a5	a6	Ajusted R^2	N
January	-0.08	0.22	0.22	0.44	0.76	-0.78	-	0.964	2211
	(-6.9)	(17.7)	(12.9)	(14.8)	(55.3)	(-22.1)	-		
April	-0.03	0.34	0.23	0.32	0.74	-0.68	-	0.952	2757
	(-1.7)	(16.2)	(18.4)	(9.4)	(59.9)	(-27.6)	-		
July	-0.04	0.34	0.23	0.39	0.68	-0.66	-	0.945	3115
	(-2.9)	(16.3)	(21.1)	(12.8)	(58.5)	(-25.2)	-		
October	-0.05	0.29	0.25	0.36	0.69	-0.74	-	0.947	2478
	(-3.1)	(16.3)	(17.9)	(11.0)	(49.8)	(-26.9)	-		

Note: Data period is from 1997 to 2003. T statistical value is shown in parentheses.

Figure 4. Estimated Monthly Global Solar Radiation (Tokyo)



Note: This figure shows a monthly value counted up hourly estimated value.

Global solar radiation in each AMeDAS site was estimated by applying estimation formulas of the nearest meteorological observatory. As each member's residence was from about 500 meters to 16 kilo meters away from the nearest AMeDAS site (an average of 8 kilo meters), it was not unreasonable to assume an estimated value in the nearest AMeDAS site as that of each residence in evaluating the trend of performance.

As global solar radiation and total solar radiation for a panel are different, due to direction and tilt of a panel, it is necessary to estimate the latter. In this paper the methods described in Erbs et al (1982) and Perez et al (1990) were used to estimate total solar radiation for each panel from global solar radiation.

Hourly PV output was calculated by formula (2). Performance ratio was set at 0.7, based on results of Jahn and Nasse (2003). The loss is mainly caused for two reasons: 1) difference between STC and actual condition; and 2) loss in transforming alternate-current power through a power conditioner. Generally it is said that the performance ratio shows seasonal variation due to the temperature characteristic of a PV cell, but in this paper it was set at the same value for a year, according to IEA/PVPS Task 2 database mentioned above.

$$P_E = I * C / G * K \qquad (2)$$

P_E: Estimated PV output (kWh/h)

I: total solar radiation ($kWh/m^2/h$)

C: capacity (PV output at STC) (kW)

G: solar irradiance at STC = 1(kW/m^2)

K: performance ratio

The performance of the PV system was evaluated as monthly or annual "PV output index" as follows:

$$\text{PV output index} = P_A / \sum_i P_{Ei} * 100 \qquad (3)$$

P_A: Actual PV output (kWh/month or kWh/year)

Suffix i shows each hour in a month or a year.

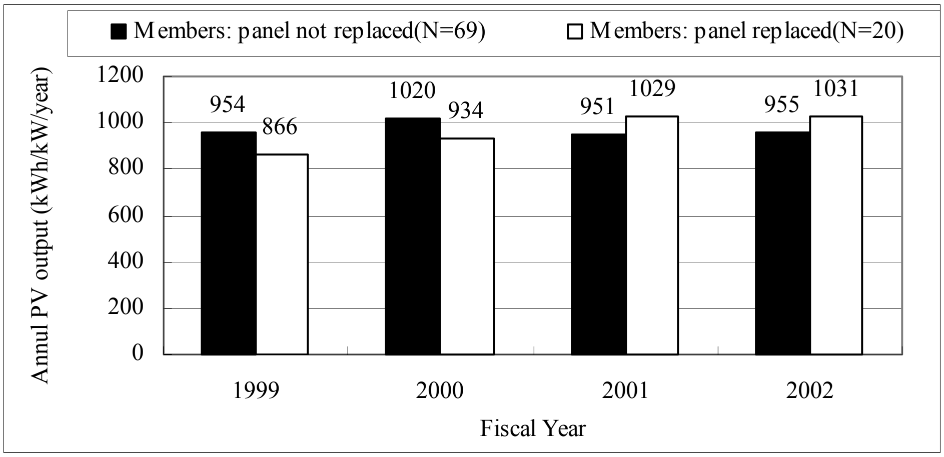
Result

Annual PV output from 1999 to 2002 is illustrated in **Figure 5**. PV output in 2002 was 955 kWh/kW/year for members whose panel was not replaced (we call them "Group N") and 1,031 kWh/kW/year for members whose panel was replaced ("Group R"). PV output of Group R increased in 2001, despite the decrease in Group N because of replacement.

Annual PV output index from 1999 to 2002 is illustrated in **Figure 6**. The index of Group N was 101 in 2001. Degradation of performance was generally not observed during this period. Though the index in 2002 decreased by three points from the previous year, it falls within the estimation error range. The index of Group R increased by twenty-one points in 2001 due to replacement.

Figure 7 shows the distribution of the annual PV output index and the difference of index of members from 2001 to 2002. Out of ninety-one members sixty-six members were in a range from –5 to –1, which does not necessarily mean the graduation of performance as mentioned above. However, in a few cases, a large decrease in index was found. For example, the index of Member A was gradually decreasing from 1999. The indexes of Member B and Member C (Group R) rapidly decreased in 2002 (see **Figure 8**).

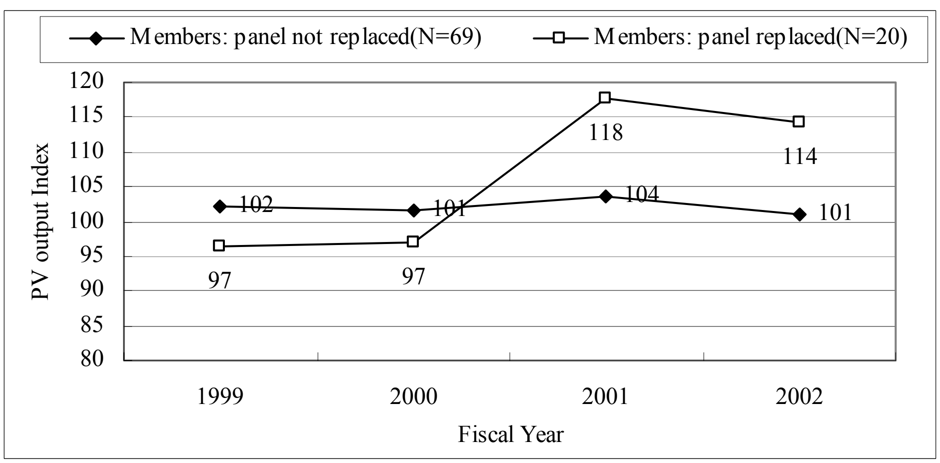
Figure 5. Annual PV Output



Note 1: As almost all members did not investigate PV outputs between October 2000 and May 2001, annual PV output was simply calculated by multiplying average daily PV output by number of annual days.

Note 2: All PV modules of "members: panel replaced" were replaced between December 2000 and March 2001(late FY2000).

Figure 6. Annual PV Output Index



Performance degradation in the system of Member C seemed to be caused by the construction of an apartment building on the southern side of the residence according to the owner. As shown in **Figure 9**, the index decreased in winter.

As there were no changes in the environment of the systems of Member A and B, we did field investigations with a manufacturer to check the systems. In the result, deterioration was found in several modules respectively. According to the manufacturer's report, the deterioration was due to technical problems, such as defective continuity caused by loose contact of lead wires, defective by-pass diode, and defective soldering on cell.

Figure 7. Distribution of Annual PV Output Index and the Change from the Previous Year

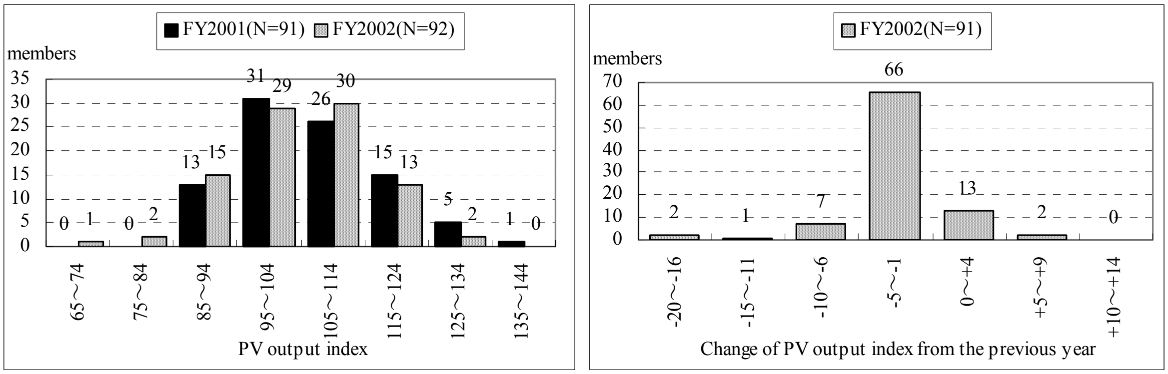
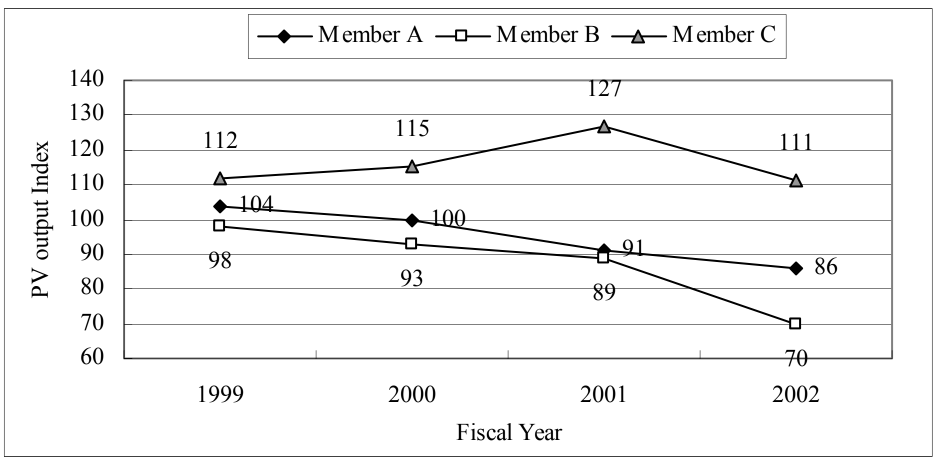


Figure 8. Examples of Performance Degradation



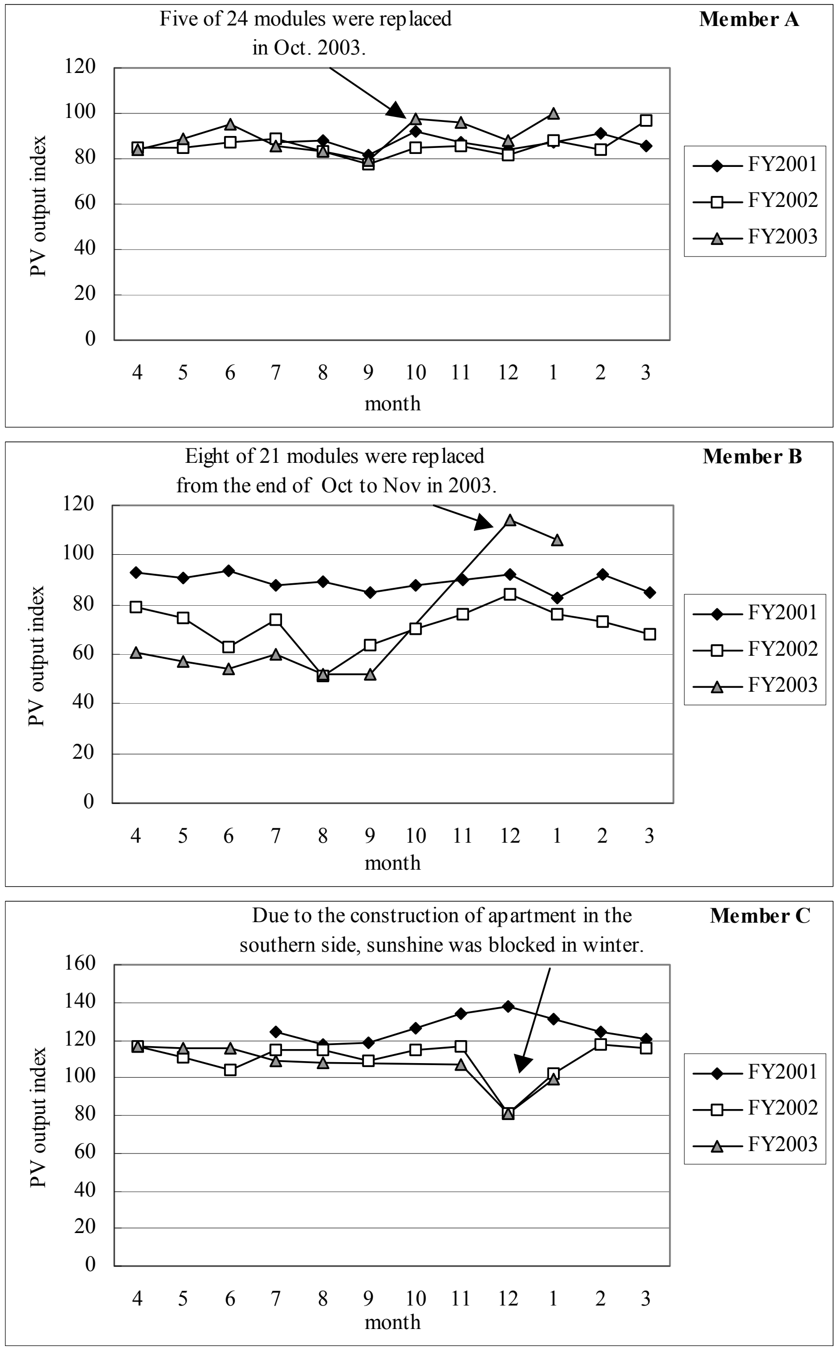
Note: Member A and B belonged to Group N (Members: panel not replaced).
Member C belonged to Group R (Members: Panel replaced).

From October to November 2003, those modules were replaced by the manufacturer for free. The effect was shown as a recovery of PV output index.

Conclusion

We discuss in this paper the method to evaluate the performance of PV systems without additional cost to PV owners, which was applied to an activity of the CELC, a group of PV owners.

Figure 9. Monthly PV Output Index (Example of Degradation)



Since June 2001 each member of the CELC has checked PV output once a month by watching an indicator on a power conditioner and reporting the value to JYURI. To evaluate actual PV output, PV output was estimated from meteorological data by newly developed formulas and outcomes of existing studies. Performance of PV systems was evaluated as monthly or annual “PV output index”, which was an actual PV output at the time of setting an estimated value to 100.

Annual PV output index of members whose panels were not replaced was 101 in 2001. Degradation of performance was generally not observed between 1999 and 2002. Though the index in 2002 decreased three points from the previous year, it falls within the estimation error range. However, in a few cases a large decrease of index was found.

For two members, we did field investigations with a manufacturer to check the systems. In the result deterioration was found in several modules respectively. From October to November 2003, these modules were replaced by the manufacturer for free. The recovery of monthly index after replacement was apparent.

The method we propose above was cost-effective to evaluate the performance of PV systems, once a tool for estimation was developed. Detecting deterioration will be improved by continuing the activity, and it will be possible to provide how to check performance and what causes decreasing performance to present and future PV owners.

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